INNOVATIVE TECHNOLOGY
Summary Report

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Advanced Tensiometer for Vadose Zone Monitoring

Characterization, Monitoring, and Sensor Technology Crosscutting Program and Subsurface Contaminants Focus Area

Prepared for
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Office of Environmental Management
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INNOVATIVE TECHNOLOGY
Summary Report

Advanced Tensiometer for Vadose Zone Monitoring

Tech ID 2122

Characterization, Monitoring, and Sensor Technology Crosscutting Program and Subsurface Contaminants Focus Area

Demonstrated at
Idaho National Engineering and Environmental Laboratory,
Idaho Falls, Idaho
Savannah River Site, Aiken, South Carolina
Hanford Reservation, Richland, Washington

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under "Publications."

TABLE OF CONTENTS

APPENDICES

SECTION 1

SUMMARY

Technology Summary

Introduction

U.S. Department of Energy (DOE) sites, especially those with buried waste, are required to document and verify performance assessments for stabilizing and disposing of hazardous waste; this includes preventing the hazardous constituents from contaminating groundwater. The four data sets needed to assess the movement of contaminants in the vadose zone are:

- Soil Water Potential
- Temperature
- Soil Water Content
- Contaminant Concentration

Tensiometers are well suited for measuring soil water potential. Tensiometers can also be used as suction lysimeters, i.e., pore water samplers. When they are used this way around waste disposal sites, laboratory analysis of the samples can provide early data concerning contaminant movement, if such movement occurs. Early information is important because it can enable early action that may forestall contamination of public water supplies and minimize the cost of later, perhaps more extensive, cleanup action. The soil water potential data provided by tensiometers can also be used together with neutron probe data for optimizing the placement of monitoring well locations for site stewardship programs.

The Advanced Tensiometer for Vadose Zone Monitoring (referred to hereafter as the Advanced Tensiometer or AT) was developed to overcome the limitations of conventional tensiometers. ATs are superior to conventional tensiometers primarily because ATs:

- Provide reliable soil water potential measurements at much greater depths than conventional tensiometers.
- Require less frequent maintenance than conventional tensiometers.
- Are largely unaffected by ambient temperature changes, whereas conventional tensiometers are adversely affected.

The AT operates on the same physical principle as a conventional tensiometer. It has two parts: (1) a permanently installed porous cup with a water reservoir and guide tube and (2) a removable pressure transducer. The AT is deployed by lowering it into a borehole and bringing the porous cup into good hydraulic contact with the subsurface soil. Water in the reservoir then moves through the porous cup until the pressure inside the reservoir equilibrates with the soil moisture pressure in the surrounding soil or rock. The pressure transducer measures the partial vacuum; a data logger at the surface records the measurements.

Award Winning Technology

The AT developed at the Idaho National Engineering and Environmental Laboratory (INEEL) is a 1997 R&D-100 award winner (R&D Magazine 1997).

The AT features a short water column that is isolated from diurnal temperature changes. This stabilizes the readings compared to those from conventional tensiometers. The AT is an effective instrument for monitoring when the soil water potential is in the range 0 to -800 cm water pressure. This is the energy status range with the highest hydraulic activity, and thus with the greatest potential for rapid water movement. The AT design is simple, low cost, and low maintenance. There are no moving parts and the pressure transducer is serviceable from the land surface.

The AT is a dual-purpose instrument. It is used primarily to monitor soil water potential, but it can also be converted readily for the collection of soil water samples. In that case, the pressure transducer is removed and replaced with a sampling chamber. A vacuum is applied to the inner guide tube to cause collection of soil water in the porous cup. The collected water can be pumped to the surface periodically or the sample chamber and sample can be removed to the surface. In either case, the collected soil water sample is typically sent to a laboratory for analysis.

Figure 1. Typical Advanced Tensiometer for Vadose Zone Monitoring (AT) installation with solar-powered data logger.

Advantages of the AT (as compared to conventional tensiometers)

- Conventional tensiometers, with pressure gauges located at the land surface, have a practical depth limitation and are adversely affected by barometric pressure and ambient temperature changes. The AT overcomes the depth limitation of conventional tensiometers and is largely unaffected by ambient temperature changes at the surface. The AT enables soil water potential measurements to unlimited depths (at the time of this writing, ATs have been installed to 146 meters below land surface, 60 meters below land surface for the portable version), whereas conventional tensiometers are only useful at depths of less than 7 meters (approximately 3 meters in arid soils).
- The AT can be checked for proper operation *in situ*.
- The AT pressure transducer (zero and slope) can be calibrated *in situ*.
- The AT provides an order-of-magnitude improvement in the precision and reliability of soil water potential measurements (as compared to conventional tensiometers) at any depth in the unsaturated zone.
- The AT can operate when the surface temperature is less than 0º C if the porous cup and transducer are below the frost depth. This reduces field maintenance requirements and permits monitoring throughout the year to capture soil moisture changes caused by episodic events such as snow melt.
- The pressure transducer in the AT can be removed and replaced in the field, thus providing temporary access for other instruments or sampling devices (e. g., neutron probe, thermocouple psychrometer, water sample collector).
- Several of the characteristics cited above reduce the maintenance and servicing needs of the AT as compared to conventional tensiometers. ATs have been operated continuously in the field for more than five years.
- ATs have operated attended (no field maintenance) for periods longer than one year and as short as six weeks.

Disadvantages of the AT (and conventional tensiometers)

- Tensiometer measurements are point measurements. Apart from other tensiometer measurements, no single tensiometer measurement can describe the overall status of an extended soil volume.

Potential Markets

The DOE has numerous sites, including the following, where the application of ATs can provide important data concerning the movement of water and accompanying hazardous material in the subsurface.

- Idaho National Environmental and Engineering Laboratory (INEEL)
- Oak Ridge Reservation (Oak Ridge)
- Hanford Reservation
- Savannah River Site (SRS)

The AT has additional market potential in the following areas:

- Geotechnical engineering
- Waste management
- Mining
- Agricultural research
- Agricultural irrigation
- Water resource management

These AT applications are described in greater detail in Section 4.

Demonstration Summary

This demonstration summary covers the period March 1997 through December 2001.

Dozens of ATs have been demonstrated at numerous sites representing several geologic and climatic environments. In many cases, the ATs are still actively monitoring the soil moisture potential. The demonstration sites include the following:

- INEEL Research Center in Idaho Falls, Idaho
- Box Canyon research site near Arco, Idaho
- Hell's Half Acre research site in Idaho
- Idaho Nuclear Technology and Engineering Center at the INEEL
- Radioactive Waste Management Complex at the INEEL
- Savannah River Site, Aiken, South Carolina
- U. S. Nuclear Regulatory Commission (NRC) low-level radioactive waste demonstration project at Maricopa Agricultural Center[1], Casa Grande, Arizona
- Bear Creek site at the DOE Oak Ridge Reservation, Oak Ridge, Tennessee
- Buried Waste Test Facility at the Hanford Reservation, near Richland, Washington
- University of Idaho, Moscow, Idaho, Troy Research Site
- University of California, Davis

The capabilities of the AT have been documented in a number of separate demonstrations, some of which are described more fully in Section 3 of this report and in the scientific literature (Hubbell and Sisson 1996, Hubbell and Sisson 1998, Sisson and Hubbell 1999). The first field demonstrations were performed in 1997 at the INEEL. The published results from those demonstrations document the basic performance characteristics of the AT and show that its performance and maintainability are superior to that provided by conventional tensiometers. The most recent demonstrations (applications at the SRS and Hanford sites) are full-scale applications of the AT to characterize and monitor soil water and/or associated contaminant transport at specific DOE facilities.

Commercial Availability

North Wind Environmental, Inc., of Idaho Falls, Idaho, entered into an exclusive license agreement regarding the manufacture and sale of all products covered by the claims of U. S. Patent No. 5,915,476, including the AT and PT, in November 2000. The initial license covers application at the INEEL site only,

[1] The Maricopa field site is operated by the University of Arizona, Tucson, AZ.

but it can be extended for applications at other federal sites upon request. North Wind operates on a contract basis, providing geosciences consulting and subsurface characterization services. North Wind has constructed and installed ATs and is available to reduce and analyze tensiometer data.

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://em.doe.gov/ost under "Publications." The Technology Management System, also available through the OST Website, provides information about OST programs, technologies, and problems. The Advanced Tensiometer for Vadose Zone Monitoring (AT) is identified by OST Tech ID 2122.

Additional information on the AT and related technologies (Portable Tensiometer, Deep Tensiometer, and Direct Push Waste Zone Tensiometers) is available from the INEEL Technology Catalog at http://tech.inel.gov.

SECTION 2

TECHNOLOGY DESCRIPTION

Overview

Tensiometers measure soil water potential, i. e., the potential energy status of water in soil. The soil water potential indicates how tightly water is held by soil or rock. As the water content of the soil surrounding a tensiometer decreases, the potential energy level of the soil water decreases relative to that of the water in the tensiometer, and water moves from the tensiometer into the surrounding soil. If the soil surrounding the tensiometer receives additional water (e. g., by infiltration), the soil water potential increases and soil water moves from the soil into the tensiometer, thereby increasing the potential energy of the water in the tensiometer. The potential energy of the water includes the pressure head and elevation head (analogous to hydraulic head) and is used to calculate hydraulic gradients in the vadose zone. Multiple tensiometers placed at various locations and depths can help hydrologists estimate fluid movement between the land surface and the water table.

A tensiometer consists of a sealed tube filled with water, a porous cup on one end of the tube, and a pressure sensor (vacuum gauge) connected to the water chamber. The porous cup is placed in the soil, with good hydraulic contact between the water in the tube and moisture in the soil surrounding the porous cup. Relatively dry soil tends to pull water from the tube through the cup. Only a minute amount of water is actually withdrawn, however, since the tube is sealed. The pulling effect of the dry soil places the water in the tube under tension, thus creating a measurable sub-atmospheric pressure (partial vacuum) in the tube[2]. Higher moisture in the soil produces correspondingly less tension in the tube, and completely saturated soil registers substantially zero tension, i.e., atmospheric pressure. In this way, changes in soil moisture potential can indicate relative changes in soil water content. When a tensiometer is installed below the water table, it functions as a piezometer, measuring the hydraulic head at the point of placement.

How AT works

The AT operates on the same physical principle as a conventional tensiometer. It has two parts: (1) a permanently installed porous cup with a water reservoir and guide tube and (2) a removable pressure transducer. The AT is deployed by lowering it into a borehole and bringing the porous cup into good hydraulic contact with the subsurface soil. Water in the reservoir then moves through the porous cup until the pressure inside the reservoir equilibrates with the soil moisture pressure in the surrounding soil or rock. The pressure transducer measures the partial vacuum; a data logger at the surface records the measurements.

Data from several tensiometers at different locations and depths support calculation of the hydraulic gradients at various points in the subsurface. This information on the forces that influence the direction and magnitude of water movement in the subsurface allows hydrologists to estimate fluid movement between land surface and the water table. This is information that is not easily ascertained by other means (Hillel 1982). In addition, when coupled with chemical analysis of soil water samples collected from the same locations (as described above) to establish the concentrations of any hazardous materials that may be dissolved in the soil water, the gradient information enables estimation of the movement of that hazardous material between the land surface and the water table. Examples of hazardous materials that may be of concern at DOE sites include chlorinated hydrocarbons, toxic metals, and tritium and/or other radionuclides.

[2] The terms soil water potential, soil water pressure, and soil water tension are used interchangeably here and in the scientific literature pertaining to tensiometers.

Overall Process Definition

Two types of ATs are available: one for permanent installation and a portable model. The permanent model has been tested to depths of more than 146 meters below ground surface; the portable model to depths as great as 60 meters. There are no known depth limitations; both models are expected to perform well at even greater depths.

The AT for permanent installation, shown in Figure 2, has a porous cup (ceramic or stainless steel), water reservoir, and outer guide tube that are permanently installed, with a pressure transducer and inner guide pipe that can be removed. The tensiometer can be installed to nearly any depth below ground surface. The transducer can be calibrated in place without removing it to the land surface, and it can be removed and replaced if it becomes inoperative. The tensiometer can be de-aired and refilled with water from the land surface in a few seconds. Placing the transducer at the bottom of the borehole increases the time between necessary de-airings and reduces the diurnal measurement variations that are characteristic of (conventional) tensiometers that have the pressure transducer at the land surface.

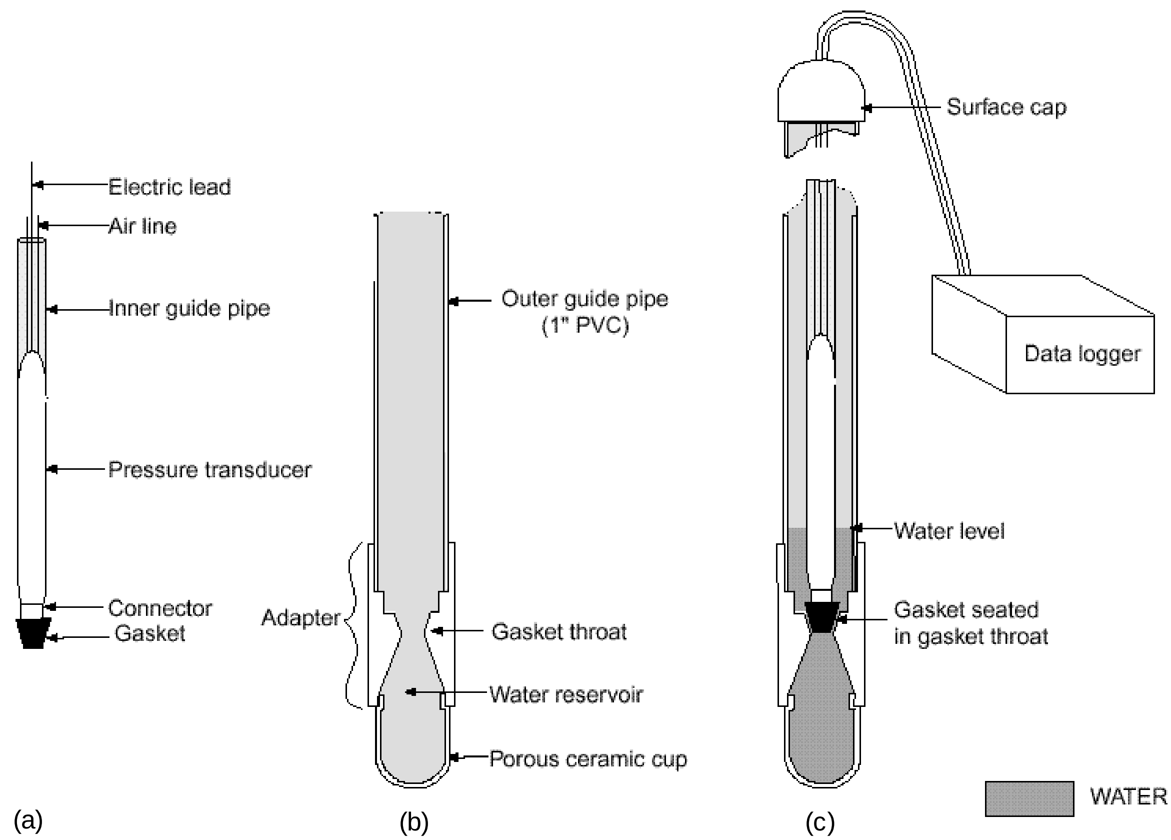

Figure 2. Advanced Tensiometer assembly drawing (not drawn to scale): (a) inner guide pipe and pressure transducer assembly, (b) outer guide pipe and porous cup assembly, (c) fully assembled advanced tensiometer.

The pressure transducer assembly has a single-hole rubber stopper or gasket on the bottom, a connector that attaches the stopper to the pressure transducer, and an inner guide pipe (polyethylene tubing or 1/2 inch Schedule 40 PVC for shallow applications) that extends to land surface [Figure 2(a)]. The connector allows pressure to be transmitted from the end of the stopper to the diaphragm of the transducer. The stopper size is chosen to firmly connect with the gasket through of the adapter [Figure 2(b)]. Electrical leads and an air line from the pressure transducer (gauge pressure) are contained within the inner guide pipe and connect to a data logger [Figure 2(c)].

The permanently installed porous cup assembly consists of a porous cup bonded to a plastic adapter and PVC pipe that extends to the land surface [Figure 1(b)]. The adapter is machined to provide a seat to the pressure sensor (gasket throat), fitting between the porous cup on the bottom and the outer guide pipe on the top. The adapter is attached to commercially available tubing (outer guide pipe), which extends to land surface. A surface cap is placed on top of the outer guide pipe at land surface. The advanced tensiometer [Figure 1(c)] is formed by sliding the inner guide pipe assembly, i. e., the entire assembly shown in Figure 1(a), inside the outer guide pipe assembly [Figure 1(b)] until the stopper (gasket) seals into the adapter.

As noted earlier, the AT can also be converted readily for collection of soil water samples. In that case, the pressure transducer is removed and replaced with a sampling chamber. A vacuum is applied to the inner guide tube to cause collection of soil water in the porous cup. The collected water can be pumped to the surface periodically or the sample chamber and sample can be removed to the surface. In either case, the collected soil water sample is typically sent to a laboratory for analysis. The results are useful for showing the presence of absence of contaminants such as tritium.

The portable version of the AT, shown in Figure 3, can be installed at nearly any depth and operated for extended time periods without field maintenance. It has a longer response time than a conventional tensiometer, because of the smaller contact area between the porous cup and the soil, and it must be removed to the land surface to service or calibrate.

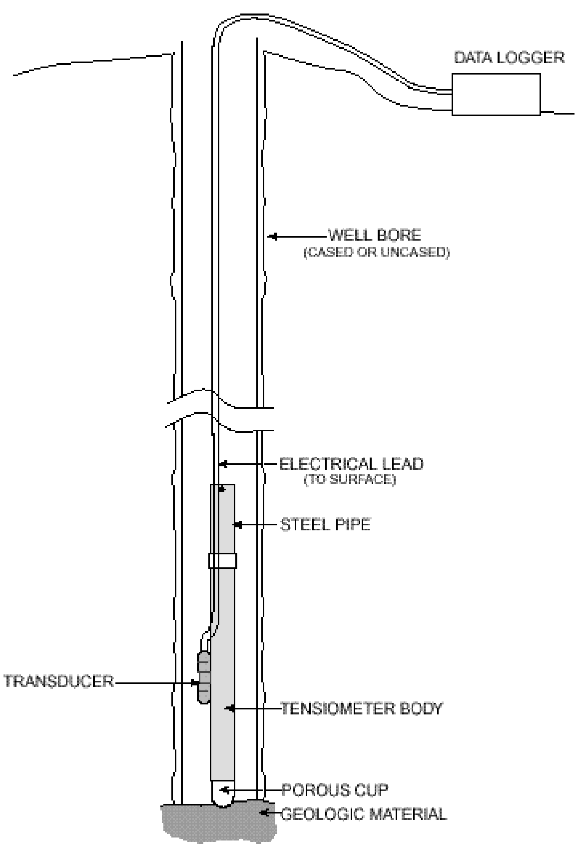

Figure 3. Schematic showing field use of a portable version of the Advanced Tensiometer.

The Portable Tensiometer (PT) for Vadose Zone Monitoring can be used for both reconnaissance measurements and long-term monitoring in wells, at depths that have not been possible previously. The PT can be used during drilling of boreholes to obtain measurements at specific depths to allow planning for placement of instrumentation. A PT can be used as a survey instrument, to measure soil water potential at the bottom of boreholes at any depth. The low cost of the PT allows several instruments to be placed in multiple boreholes. The PT with a pressure transducer and data logger allows continuous measurements over extended times. Soil water potential changes over extended periods of time, such as the passing of a wetting front or the formation of perched water, can be monitored at depth. A number of other embodiments of the AT and PT are described in the patents cited in Section 4 of this report.

Data logging and capability for remote data downloading

A variety of automated data loggers can be used to collect the tensiometer data, or an instrument technician can manually record measurements in the field. Commercial battery-powered data loggers have the capability to record measurements from a single tensiometer or multiple tensiometers, and, upon electronic command, to transmit the measurement data to a remote personal computer via an internal modem and commercial telephone service. A typical data logger installation includes (for example) a Campbell Scientific 23X Data Logger (12 differential analog inputs) with modem, battery, cellular telephone, and enclosure. The typical installation also includes a tripod and solar panel for battery recharge. Such installations are capable of unattended operation for periods lasting approximately one year.

System Operation

Installation

ATs can be installed by several techniques. One is by drilling a hole by hand to the desired depth and then installing the instrument. The second is to drill a hole using a conventional drill rig such as hollow stem auger and placing the AT through the hollow stem. A third technique is to use conventional rotary holes for boreholes that stay open following drilling. In some geologic settings, single ATs can be installed using a cone penetrometer rig (direct push technology[3]). The installation method depends heavily upon the geologic materials at the site and the conventions for drilling at the site.

ATs can be installed in any uncased borehole having a diameter greater than 3.6 centimeters, although versions have been constructed with diameters as small as 2.2 centimeters. The porous cup, adapter, and outer guide pipe are assembled at land surface and lowered down the borehole to the desired monitoring depth. The AT can be fully assembled at the land surface and lowered down the borehole or it can be assembled as it is lowered into the borehole. The outer guide pipe should be kept straight in the borehole so the transducer will go down without binding and the stopper can make a good connection with the adapter. The borehole is typically backfilled with a permeable material such as hydrated silica flour in contact with the porous cup and with low permeable materials such as bentonite above and below the monitored depth. Native fill may be used as backfill where it is available and suitable. Backfill techniques are described by Cassel and Klute (1986).

An AT is activated by filling the water reservoir with water and seating the stopper (gasket) into the adapter throat. About 100 milliliters of water is poured between the inner and outer guide pipes and the inner guide pipe assembly is raised a few centimeters to allow the water to fill the porous cup and adapter (Figure 2c). The weight of the inner guide pipe assembly and transducer presses the stopper (gasket) into the adapter and the soil water pressure also helps hold the stopper in place.

Multiple ATs can be installed in a single borehole; this type of installation is preferred at most DOE sites. The number of ATs to be placed in a borehole is limited by the depth of the installation and by the size of the AT and the backfill installation. As few as one and as many as seven ATs have been placed in a single borehole to depths of over 130 meters. A typical multiple-AT installation is illustrated in Figure 6, Section 3. ATs have been placed in rock (basalt and sandstone), sand, gravel, silt, clay, and saprolite. Most ATs have been placed in the arid west. ATs have operated at sites with as little as 200 mm/yr precipitation. So far, fewer ATs have been placed in the east at sites like the Oak Ridge Reservation and the Savannah River Site.

Maintenance

Field maintenance requirements include refilling the tensiometer with water and periodically checking the transducer calibration. A small volume of water (about 250 ml) is poured into the outer guide pipe

[3] For additional information, search the INEEL Technology Catalog (http://tech.inel.gov) for “direct push”

periodically to fill the upper reservoir, so water is available for refilling the lower reservoir. Approximately once every three months, the tensiometer is refilled with water by lifting up the inner guide pipe and pressure transducer portion and allowing water to flow from the upper reservoir into the porous cup and adapter portion of the instrument. Then, the inner guide pipe and pressure transducer portion is pushed down and the instrument is back in operation. Six or seven instruments can be refilled with water in 10 to 15 minutes. ATs at some sites have operated more than a year without refilling.

The transducer zero point and slope should be checked and recorded periodically to track any drift in the transducer performance. This takes about 15 minutes per instrument.

The data loggers must be downloaded periodically as well, either in the field or under remote control if equipped with a modem and telephone service. Downloading the data logger is generally a 10- to 15-minute operation. The data can be read and analyzed using standard software such as Microsoft Excel.

Personnel Requirements

Generally, two or three people are required to install ATs and place backfill material. Following two days of on-the-job training, the routine tasks involved in installing, maintaining, and downloading data from the ATs can be performed by persons trained as instrument technicians. Detailed planning of AT installations for determining/monitoring soil moisture in the vicinity of a hazardous waste storage or disposal facility requires the supervision a professional geohydrologist or equivalent. Analysis of the data provided by such AT installations also requires a professional geohydrologist or equivalent.

Secondary Waste Stream Considerations

The secondary waste stream considerations associated with the installation and application of ATs have some similarity to those of the baseline. Unless the ATs can be installed by direct push methods, both have investigation-derived waste associated with the drilling of boreholes. In addition, the baseline generates secondary waste related to groundwater sampling and laboratory analysis of the groundwater samples.

SECTION 3

PERFORMANCE

Demonstration Plan

As noted earlier, the capabilities and performance of ATs have been tested, demonstrated, and employed in a number of separate demonstrations. The sites included a variety of geologic and climatic conditions ranging from the arid basalt and sediments of Idaho and Hanford to the moist clays and sands of the Savannah River Site. The major objectives of the tests and demonstrations were to establish, extend, and evaluate the performance capabilities of the technology. The characteristics of principal interest included:

- Accuracy
- Precision
- Response time
- Reliability
- Durability
- Maintenance requirements.

Demonstrations and results from the INEEL, SRS, and Hanford sites are detailed in the next subsection. In each case, the AT performed better in the above areas as compared to conventional tensiometers.

Results

Comparison of Advanced Tensiometer and Conventional Tensiometer Performance at the INEEL

Figure 4 shows 6 days of soil water potential data from an AT and a conventional tensiometer (Soilmoisture Equipment Corp., Santa Barbara, CA) installed in a single borehole at 1.3 meters below ground surface (bgs). The AT soil water potential readings stabilized to about -440 cm in one day, whereas those from the conventional tensiometer varied between approximately -400 and -490 cm each day.

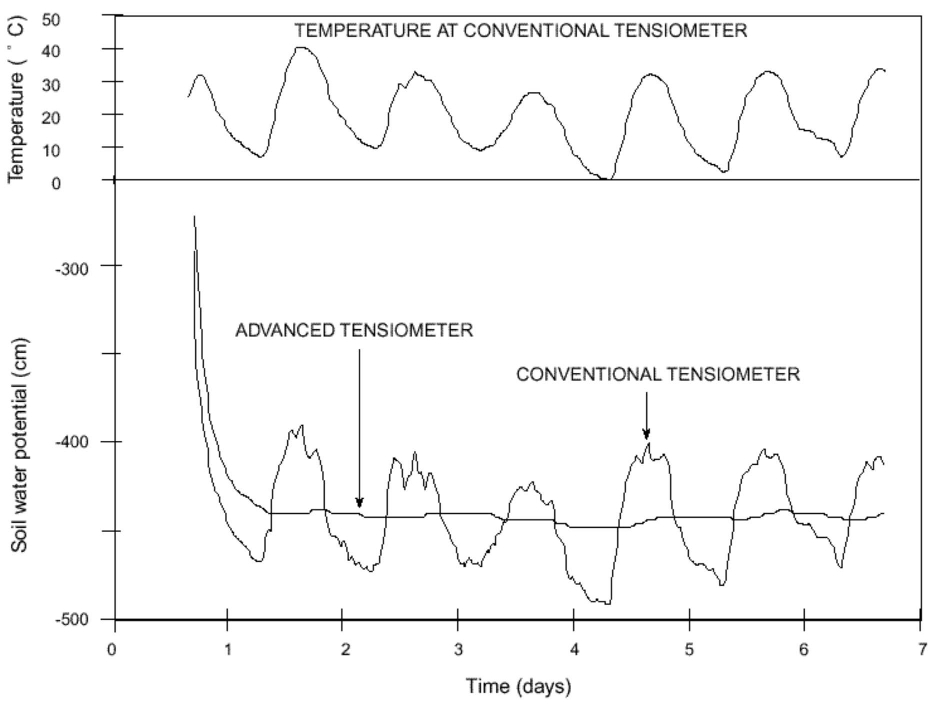

Figure 4. Soil water potential from advanced and conventional tensiometers over a six-day period.

The large oscillations in the conventional tensiometer (CT) readings are caused by temperature effects on the pressure transducer, expanding and contracting air in the headspace above the water column, and expansion and contraction of tensiometer materials—despite the fact that the transducer for the CT was covered with 1.2-cm thick plastic insulation and reflective foil. The diurnal variations seen with the CT make it difficult to see subtle short-term soil water potential changes. For example, the soil water potential measured by the AT increased only 8 cm from day 4 through day 6, whereas that measured by the CT had a range of more than 90 cm in the same period. The data show that the AT, with its short reservoir and pressure transducer placed at the lower extremity of the tensiometer, well below ground surface, has much smaller diurnal variations and much more stable tensiometer readings than the CT. (We assume, of course, that the AT values are correct or, more properly, should be more reliable and therefore taken as correct.)

Evaluation of Long Term Stability

The long-term stability of a portable AT emplaced at 6 meters bgs was evaluated in a 233- day period between 21 February 1995 and 12 October 1995 (Hubbell & Sisson 1996). The results, shown in Figure 5, show that the AT was capable of providing stable readings at depths applicable to the management of buried waste facilities. The sharp peaks observed on test days 0, 44, and 212 were caused by retrieving the tensiometer, opening it to refill it with water, and then emplacing it for additional soil moisture potential measurements.

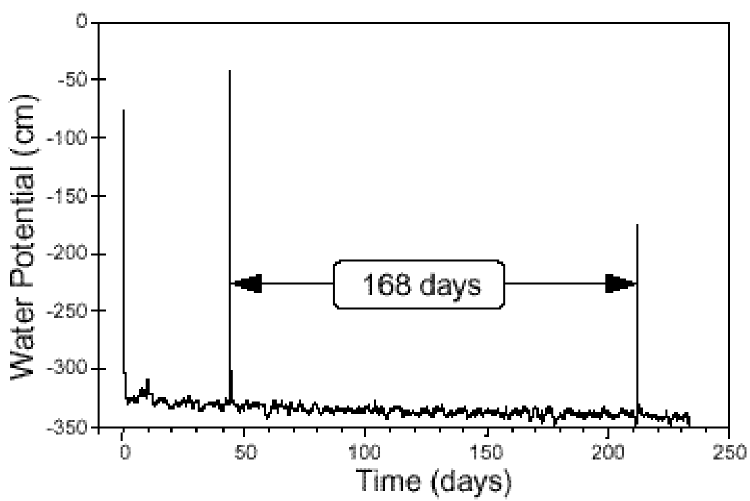

Figure 5. Soil water potential recorded by a portable Advanced Tensiometer emplaced at 6 meters below ground surface.

A linear regression fit of the data from days 44 through 212 indicated the soil water potential decreased at a rate of 0.051 ± 0.001 cm/day during that period. This decrease may be caused by evapotranspiration, deep drainage losses, or water level decline in the tensiometer. The small fluctuations in measured soil water potential about the slowly decreasing long-term trend line indicate a measurement noise level of approximately ±10 cm. This level of noise may be caused by barometric pressure effects and temperature effects on the data logger, rather than actual variation in the potential or measurement variation at the transducer. Surface temperature varied between -7 and 90 °F during the evaluation period.

Evaluation of Advanced Tensiometer Monitoring at Depth in Porous Rock and Sediment

Part of the evaluation of ATs for application in porous rock and sediment was performed at the INEEL Research Center (IRC) in fall 1995 through early spring 1997. In September 1995, well IRC 3 was drilled in Snake River Plain basalt to a depth of 15.2 m using the air rotary drilling technique with a 14.9-cm-diameter bit. The drilling site had loam and alluvial sediment extending from the land surface to a depth of 2.7 m and basalt from 2.7 to 15.5 m (Figure 6).

As shown in Figure 6, ATs were located at the sediment-basalt contact, adjacent to non-fractured basalt, fractured basalt, and “moist” or “wet” non-fractured basalt based on examination of driller's, video, caliper, gamma, and neutron logs. During the installation of the tensiometers, the well was backfilled as outlined in Cassel and Klute (1986). Loam was used to backfill most of the borehole; bentonite was used to isolate the monitored intervals. The shallowest tensiometer (2.7 m bgs) was adjacent to gravel at the sediment-basalt interface; the four deeper tensiometers were located adjacent to dense or fractured basalt. The tensiometers were filled with water at the beginning of the test in June 1996, in mid-October, and at the end of the test in February 1997. The results showed the tensiometers operated satisfactorily for more than 3 months between fillings with water.

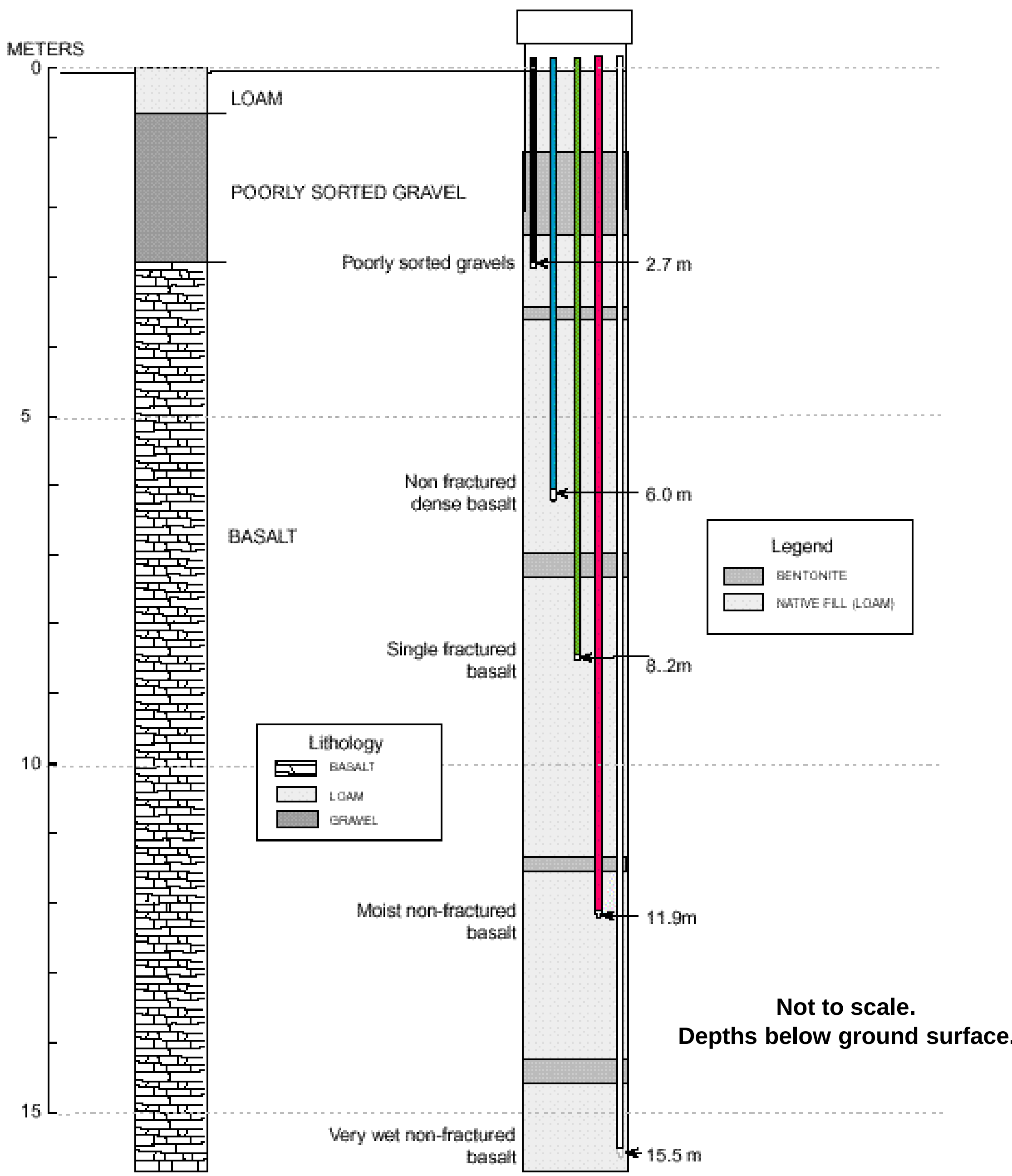

Figure 6. Geologic log and completion diagram for Well IRC-03.

The AT measurement results, from Well IRC-03, for November 1995 through March 1997, are presented in Figure 7. The tensiometers placed in basalt showed an initial period (a few hours to days) during which the tensiometer came into equilibrium with the loam used for backfill and a longer succeeding period (weeks) in which the loam came into equilibrium with the surrounding basalt. The four deepest tensiometers (at 6- to 15-m depths) indicated nearly constant values over the period of measurement after equilibrium was achieved. The 2.7-m tensiometer indicated a drying trend, from approximately -50 cm to -220 cm, from March to December 1996, and then a pronounced wetting event caused by snowmelt in December 1996.

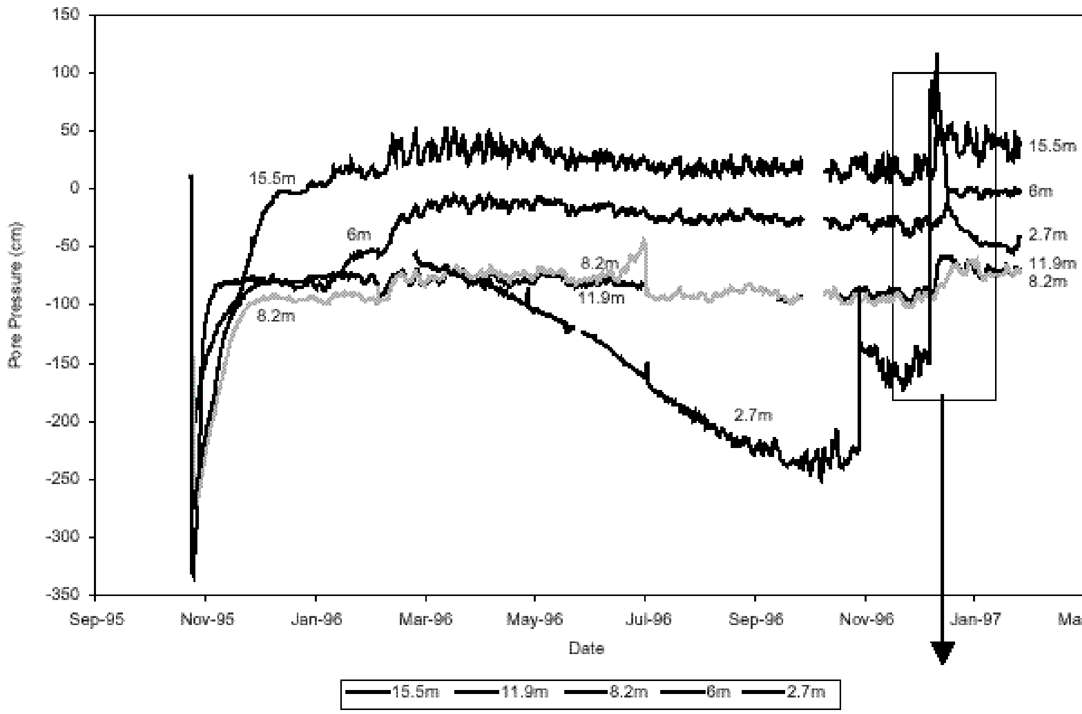

Figure 7. Soil water potential data from Well IRC-03.

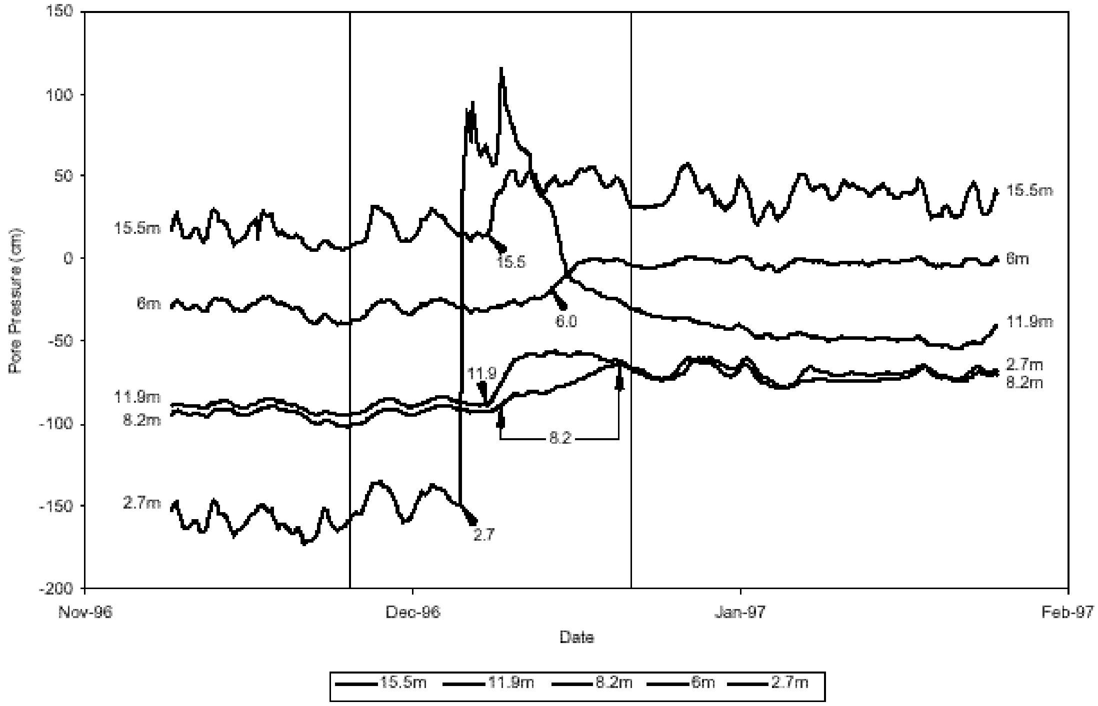

Figure 8. Detail of soil water potential data for the December 1996 infiltration event in Well IRC-03.

As indicated in Figures 7 and 8, the wetting front from the snowmelt passed from 2.7 to 15.5 m bgs in only a few days. However, the sequence of tensiometer responses indicated preferential flow paths within the basalt. Following the formation of perched water at 2.7 m at the basalt-sediment interface, the water potential increased first at the 11.9 and 15.5 m depths and then a few days later at the 6 m and finally the 8.2 m depth. The most rapid change in water potential caused by infiltration was observed at 15.5 and 11.9 m, adjacent to moist to wet non-fractured basalt. The most gradual response was recorded by the tensiometer at 8.2 m. Apparently, after the snowmelt moisture passed through the topsoil, it passed first through fractures in the basalt without coming in contact with the tensiometers at the middle depths. Only later, after it had reached the 15.5-m level, did the moisture wet those middle strata and cause responses from the tensiometers at the middle depths. The data showed that infiltration occurred rapidly through the basalt, with the velocity of the water pressure pulse ranging from 1 to 3 m/day.

Similar wetting episodes were observed after snowmelt and precipitation events in January and March 1996. The January event indicated an increase in water potential of about 15 cm at the 6- and 15.5-m depths; the March event caused a 20-cm increase. Following the wetting episodes, the tensiometer measurements showed decreases in water potential until the wetting event in December 1996. The water potentials increased in response to infiltration events and subsequently decreased slowly. This observation is consistent with wetting caused by infiltration through preferential flow paths followed by (slower) drainage through the basalt matrix.

Overall, the results showed the ATs are useful for monitoring moisture conditions in porous rock and sediments at depths appropriate to waste disposal sites.

Deployment of Advanced Tensiometers as Part of the Vadose Zone Monitoring System at SRS

Twelve ATs were deployed as part of a vadose zone monitoring system (VZMS) at the E-Area Disposal Facility[4] (EADF) at the Savannah River Site, Aiken, SC. The facility consists of both shallow trenches and concrete disposal vaults and is located adjacent to a burial ground complex that received radioactive wastes from 1952 to 1995. Because of the proximity of older disposal units, previous tritium contamination in the groundwater masks potential contributions from the EADF. The VZMS was

[4] For low-level radioactive waste

designed (Sisson and Hubbell 1998) to overcome this limitation and meet monitoring requirements identified in DOE Order 435.1 *Radioactive Waste Management*, which requires a comprehensive monitoring program that both:
(1) validates the performance assessment [i. e., shows that radionuclide migration from the trenches/vaults does not exceed what is predicted by the performance assessment] and (2) demonstrates that leaching from the E-Area disposal units does not cause radionuclide levels in the groundwater to exceed Drinking Water Standards.

The VZMS at the Savannah River Site includes ATs to measure soil water potential, time domain reflectometers (TDRs)[5] to measure the volumetric water content of the soil, and porous cup suction lysimeters to collect soil water samples for analysis of contaminants. The data from these three types of instruments relate directly to water movement and contaminant migration from the trench disposal area. The data can be utilized to determine the contaminant flux, i. e., how fast a given contaminant is traveling through the vadose zone to the groundwater. The contaminant of primary interest is tritium because tritium is present in the waste disposed in the trenches and tritium is expected to be the radionuclide that travels fastest to the groundwater.

Instrument clusters containing one AT, one TDR, and one porous cup suction lysimeter were placed at depths of approximately 6, 12, 17, and 18 meters (20, 40, 55, and 60 feet)[6] in each of three vertical wells around the perimeter of one of the E-Area low-level radioactive waste trenches at the SRS[7]. The vertical wells were at the NE and NW corners and on the eastern side of the trench, forming a triangular pattern. This arrangement allowed the soil-water flux to be estimated (based on the gradient between the instruments and laboratory-derived hydraulic properties) and also allowed monitoring of lateral contaminant transport. The vertical wells included ATs at four different depths so that the rate at which a wetting-front is moving through the vadose zone can be used to determine the soil-water velocity, the direction of water movement, and the soil-water flux. Suction lysimeters at the bottom of four angled wells drilled under the centerline of the trench complete the monitoring system and enable monitoring of vertical contaminant transport. The angled wells are spaced approximately 30 meters apart to monitor the entire length of the trench. The contaminant flux comparable to that estimated in the performance assessment, i. e., how fast a given contaminant is moving through the vadose zone to the groundwater, is inferred from the soil-water flux and the contaminant concentration.

In the VZMS installation at the Savannah River Site (SRS), a solar-powered data logger serves the ATs and the TDRs in each of the three vertical wells. See Figure 9. The data loggers are equipped with cellular telephone links to allow direct downloading of data and calibration information to both offsite and onsite personal computers. Automated data collection began April 16, 1999 and was planned to continue for at least one year[8]. The AT inventors, Joel Hubbell and Buck Sisson of INEEL, supplied and installed the Advanced Tensiometers, suction lysimeters, and TDRs. The SRS was the first site to utilize the AT in combination with other instruments to monitor soil parameters at up to 18 meters depth in the vadose zone at a non-arid site

[5] The time domain reflectometers are sometimes also referred to as water content sensors or water content reflectometers (WCRs).
[6] These depths are just above fine-sediment zones (clays and silts) in the subsurface where moisture is most likely to collect.
[7] Neutron probe access ports were placed adjacent to each of the vertical wells. Neutron logging was used to validate the data provided by the water content reflectometers.
[8] The End User Points of Contact for the SRS AT deployment are identified in the TMS system under OST # 2122.

Figure 9. Solar-powered data loggers for three wells along the edge of a waste trench at the SRS.

Benefits. The data obtained by the VZMS installation at the Savannah River Site are being used to validate and calibrate the performance assessment for the site and to indicate the SRS low level radioactive waste disposal operation satisfies groundwater quality standards. In this way, the data may provide justification for a "No Further Action" decision concerning potential leakage of tritium (and other radionuclides) from the waste trenches; this would be a significant cost avoidance. The VZMS instruments transmit the measurement data to onsite and offsite analysts on command via cellular telephone. Over the long duration of the planned monitoring this provides a significant cost avoidance because no one has to go to the field to capture the monitoring data.

Initial Findings from the VZMS Installation at the Savannah River Site. The soil water potentials as measured by the ATs reflected expected subsurface conditions. The lowest soil water potentials (reflecting dryer conditions) were in the shallower zones; the deeper zones, nearer the capillary fringe, had higher soil water potentials. Figure 10 shows the soil water potential data obtained from the AT sensors in vertical boring #5 at all four depths in the vadose zone (from 7 to 17 meters depth). Data from the AT sensors in boring #5 are shown because this borehole contains the largest number of operative solution samplers. The solution samplers, when placed under vacuum, collect soil moisture until the vacuum equilibrates with the surrounding soil water potential. At that time, water from the soil is no longer drawn into the lysimeter collection chamber.

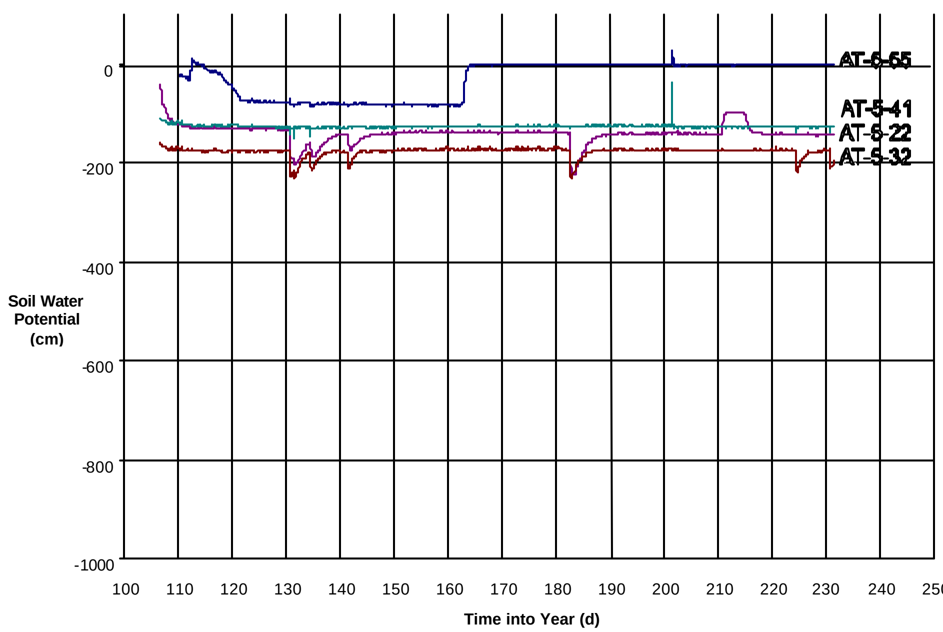

Figure 10. Advanced tensiometer data for boring #5 (AT-5)

In Figure 10, the sharp decreases in soil water potential (days 134, 141, 182, 225, and 230) occurred on days when the solution samplers were placed under vacuum to collect soil water. The ATs performed as expected, with the soil water potential decreasing as the surrounding soils became dryer during collection of soil water by the solution sampler. The step increase in the soil water potential at the deepest depth (AT_5_55 at 17 meters bgs) occurred at the time of a heavy rainfall (day # 163) that raised the water table.

All the data from the ATs in borings #5, #6, and #7 indicate that the soil water potential is relatively constant, ranging between -100 cm (wetter) to -200 cm (dryer), expected potentials for SRS soils. Furthermore, the soil water potentials appeared to be unaffected by daily or yearly infiltration events at the depths monitored. Over the first 3.5 months of monitoring the total variation in soil water potential for each of the tensiometers in the borehole was less than 100 cm.

Application of ATs in Support of the Hanford Reservation Groundwater Vadose Zone Project

In August 1999, the Pacific Northwest National Laboratory (PNNL) Hydrology Group, in support of the Hanford Reservation Groundwater Vadose Zone Project, worked with the AT inventors, James B. (Buck) Sisson and Joel M. Hubbell, to install six ATs at various depths in a 7.6-m deep lysimeter at the Hanford Buried Waste Test Facility (BWTF), near Richland, WA. Since then, those six ATs have been used continuously to monitor soil water pressures in the Hanford sediments[9]. Figure 11 shows the pressure readings of the six ATs as a function of time.

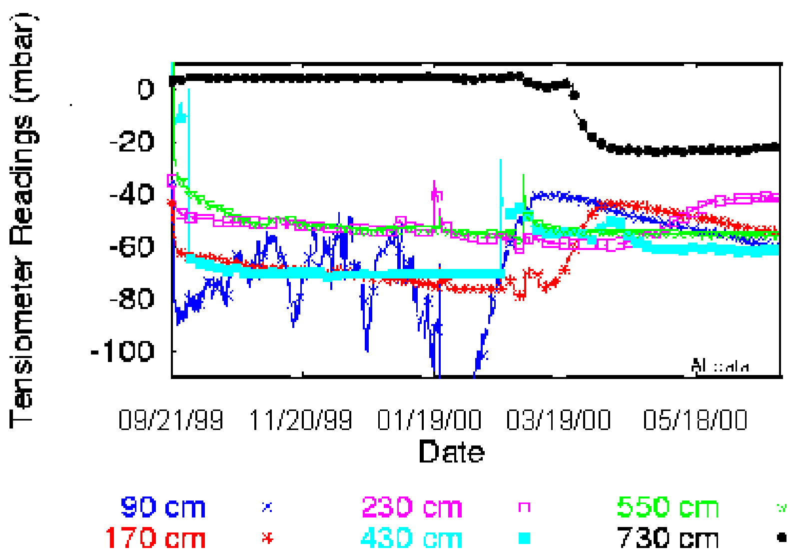

Figure 11. Advanced Tensiometer (AT) soil moisture potential readings at the Buried Waste Test Facility (South Caisson) as a function of time. The water table is at 7.4 meters below ground surface (bgs) and the tensiometers are located at 0.9, 1.7, 2.3, 4.3, 5.5, and 7.3 meters bgs.

In the past, manual tensiometers and neutron access tubes were used to document soil moisture potential and water content in this lysimeter. The investigators plan to compare the data from the ATs with that from the manual tensiometers over periods of months. According to the PNNL scientists, two advantages of the AT are its low maintenance requirements and its ability to continuously monitor the soil moisture potential in the vadose zone. As can be seen in Figure 11, the ATs at the Hanford Reservation are providing, for the first time, nearly continuous (hourly) documentation of pulses of water moving deep within the soil at that site.

[9] Additional information on this project is available at http://etd.pnl.gov:2080/vadose/tensiometer.htm

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Soil water potential measurements from several tensiometers at different locations and depths provide data required for calculation of the hydraulic gradients at various points in a subsurface volume. This information on the forces that influence the direction and magnitude of water movement in the subsurface, combined with soil water content and contaminant concentration data, allows hydrologists to estimate (predict) soil water and accompanying contaminant movement between the land surface and the groundwater. Also, because soil water potential is related to soil moisture content, ATs provide information on the actual movement of soil moisture in the subsurface. Finally, when an AT is installed below the water table, it functions as a quick response piezometer, measuring the hydraulic head at the point of placement.

Because of the capabilities listed above, the AT has several important applications at DOE sites.

1. When applied as part of a complete VZMS such as that at the Savannah River Site, ATs can provide some of the key data required for soil water and contaminant transport modeling, and for validation of such modeling. Hence ATs have important application for development and verification of performance assessments for the arrangements DOE sites are planning or already have in place for stabilizing and disposing of hazardous waste and preventing the hazardous constituents therein from contaminating the groundwater.
2. Installed around waste storage or disposal sites, ATs converted for use as suction lysimeters or pore water samplers and analysis of the samples from them can provide early information (data) concerning contaminant movement if such occurs. Early information is important because it can enable early action that may forestall contamination of public water supplies and minimize the cost of later and likely more extensive cleanup action.
3. The soil moisture potential data provided by ATs can also have important value for guiding the location of sensors and monitoring wells for optimal and efficient long-term monitoring and stewardship programs. This is most true when the tensiometer data are augmented with soil moisture data obtained by neutron probe measurements.

Competing and Complementary Technologies

The principal competition for the AT is provided by conventional tensiometers (Cassel and Klute 1986), thermocouple psychrometers (Rawlins and Campbell 1986; Rasmussen and Rhodes 1995), and heat dissipation sensors (Campbell and Gee 1986). However, only ATs and conventional tensiometers provide direct measures of soil water potential. The range of soil water potentials measured with tensiometers is 0 to approximately -800 cm of water. Thermocouple psychrometers (TCPs) and heat dissipation sensors (HDSs) measure relative humidity and heat transfer properties, respectively, at the subsurface measurement location; the soil water potential must be derived from the measured properties including temperature. TCPs perform best in very dry soils in arid regions (soil moisture potentials between -2000 and -80,000 cm of water); they do not perform well (i. e., with sufficient accuracy) in wetter soil (with soil water potentials between 0 and -800 cm of water). The principal difficulty is a fundamental one: relative humidity changes very little over the range of soil water potentials that prevail at most subsurface locations.

The operating range of HDSs is between 0 and -2000 cm of water, actually broader than that of the porous cup tensiometers, including ATs. In the case of the HDSs, instrument calibration is required to relate the measurements of heat transfer properties to soil water potential. For HDSs, the calibration depends on soil properties such as composition, particle size distribution, and compaction. These properties are often substantially different at different locations, even at a single measurement site, with adverse impact on the accuracy of the calculated soil water potential results. Additional information concerning the relative performance of the technologies that potentially compete with ATs is provided in two comprehensive vadose zone works (U. S. EPA 1993; Looney and Falta 2000).

Several other technologies provide complementary data that can be used in a Vadose Zone Monitoring System:

- Lysimeters
- Neutron probes
- Moisture sensors

The technologies identified above are complementary to each other in the sense that each provides different information and has different performance characteristics, such as range of applicability, quantitative measurement capability, and ease of use. These technologies are often used together (constituting a technology system) to characterize the movement of moisture within the subsurface. Monitoring wells with groundwater sampling and laboratory analysis comprise the baseline technology for determining whether or not moisture and accompanying hazardous materials are moving from waste storage or disposal sites and contaminating the groundwater.

Technology Applicability

- **Technology Selection Considerations.** For waste management applications, the AT (both permanent installation and portable models) has important technical and economic benefits compared to conventional tensiometers. The technical benefits include the capability to perform at the depths required (providing data and understanding not otherwise available), improved accuracy, and early warning capability. The economic benefits include decreased maintenance requirements and cost avoidance enabled by the new ability to recognize, evaluate, and fix waste isolation problems early, before serious escalation of such problems and their associated remediation costs.

- **Other Applications.** The AT and PT are applicable in several other areas in addition to waste management. Those areas include the following.

  – **Geotechnical Engineering.** Dam integrity and slope stability are affected by soil water potential, moisture content, and depth of water; the AT indicates relative changes in moisture and the depth of saturation. Its measurements also aid in assessing the effectiveness of dewatering programs.
  – **Mining.** Movement of fluids through unsaturated materials is crucial to two aspects of many mining operations: heap leaching efficiency and tailing pile stability. ATs allow automated monitoring of soil water potential, which can be related to relative water content in both settings.
  – **Water Resource Management.** Trends in soil water potential measurements are useful for evaluating evaporation and recharge to aquifers. Also, soil water potential trends may help predict whether precipitation will infiltrate the ground or flow overland—valuable information when assessing flash flood potential.
  – **Agriculture.** ATs allow quantitative evaluation and management of irrigation efficiency, saving water, power, and labor. Automated data recording and the ability to transmit data via radio or telephone provide added convenience and efficiency.

Patents/Commercialization/Sponsor

- **Patents.** The Advanced Tensiometer and technology are covered by three U. S. patents.
  – Tensiometer and Method of Determining Soil Moisture Potential in Below-Grade Earthen Soil, U. S. Patent No. 5,644,947, July 8,1997.
  – Tensiometer and Method of Determining Soil Moisture Potential in Below-Grade Earthen Soil, U. S. Patent No. 5,758,538, June 2, 1998.
  – Monitoring Well
  U. S. Patent No. 5,915,476, June 29, 1999.

- **Commercial Involvement.** In-Situ, Inc., of Laramie, Wyoming, manufactured and offered ATs and PTs for sale under an exclusive licensing agreement that began in April 1997 and continued to April 2000. North Wind Environmental, Inc., of Idaho Falls, Idaho, entered into an exclusive license agreement regarding the manufacture and sale of all products covered by the claims of U. S. Patent No. 5,915,476, including the AT and PT, in November 2000. North Wind operates on a contract basis, providing geosciences consulting and subsurface characterization services. North Wind has constructed and installed ATs and is available to reduce and analyze tensiometer data.

- **Sponsors.** Development of the AT and PT has been supported by the DOE EM Office of Science and Technology and the INEEL Laboratory Directed Research and Development Program.

- **Potential Privatization.** The most recent applications of the Advanced Tensiometer technology, at the Savannah River Site and at the Hanford Reservation, involved the participation of the INEEL inventors under DOE Work for Others agreements. Such arrangements are not far different from the ordinary business arrangements used in privatized applications of the technology. Also, in November 2000, North Wind Environmental, Inc., of Idaho Falls, Idaho, entered into an exclusive license agreement regarding all products covered by the claims of U. S. Patent No. 5,915,476, including the AT and PT. The initial license covers application at the INEEL site only but it can be extended for applications at other federal sites upon request. Assuming the market becomes large enough, privatization of the technology seems certain.

SECTION 5

COST

Introduction

This section compares the costs of applying an advanced technology approach including ATs and the baseline technology approach for characterization and monitoring of soil moisture movement in the vicinity of planned and existing waste storage or disposal sites. This is the principal current application for ATs at DOE sites. The goal is to demonstrate compliance with DOE Order 435.1, which requires both of the following: (1) a comprehensive monitoring program that validates the performance assessment, i. e., shows that radionuclide migration from the facility does not exceed what is predicted by the performance assessment, and (2) an assessment showing no significant impact to groundwater. At the SRS deployment site, the latter item was interpreted as requiring that concentrations of radionuclides (tritium) in groundwater not exceed drinking water standards at the compliance point, a well 100 meters downstream from the facility.

Although the costs of the advanced technology and baseline approaches are compared here, it is most important to note that the baseline approach does not provide the same information as the advanced technology approach. Table 1 and the following text detail the similarities and differences.

Table 1. Information provided by the advanced technology and baseline technology approaches for characterization and monitoring of soil water and contaminant movement in the vadose zone

Vadose zone parameter	Advanced technology	Baseline technology
Soil water potential	Yes, measured using ATs	Not at depths > 3 to 7 meters (10 to 23 feet) bgs
Volumetric water content	Yes, measured using TDRs	Yes, determined from TDR data
Soil water retention curve	Yes, determined from AT & TDR data	Not at depths > 3 to 7 meters bgs
Contaminant concentration	Yes, measured using lysimeters	Yes, measured using lysimeters
Soil water flux	Yes, computed from AT data & soil hydraulic properties	Not at depths > 3 to 7 meters bgs
Contaminant flux	Yes, computed from soil water flux and measured contaminant concentrations	Not at depths > 3 to 7 meters bgs
Contaminant concentration at compliance point	Yes, computed from data above	Yes, measured using sampling and analysis of groundwater wells

The advanced technology approach uses ATs to measure soil water potential, TDRs to measure water content, and suction lysimeters to measure tritium concentration in the soil water at various locations and depths throughout the vadose zone. Data from the ATs and TDRs are used to determine the velocity at which soil moisture (and dissolved contamination) moves toward the groundwater; data from the suction lysimeters are used to determine tritium (and/or other contaminant) concentrations in the soil water. The AT and TDR data combine to provide information on the soil water flux; this yields information on the contaminant flux when combined with the contaminant concentration data provided by the suction lysimeters. Together, the AT data (soil water potential) and the TDR data (volumetric water content) define the soil water retention curve. This curve is important in modeling soil water movement.

The baseline approach differs from the advanced technology approach in two important ways. First, it uses conventional tensiometers instead of ATs. The baseline approach provides complete information on volumetric soil water content. However, because the depths at which conventional tensiometers are useful are not as great as those covered by ATs (and not as great as those for which information on soil water potential is needed at typical DOE waste facilities), the baseline approach does not provide complete information on either soil water potential or soil water flux. The baseline provides information on contaminant concentration (from suction lysimeters) but, lacking information on soil water flux, it cannot provide information on contaminant flux. Hence, the second important difference: the baseline approach must employ sampling and analysis of groundwater monitoring wells to determine contaminant concentration at the compliance point.

Methodology

Cost Data

Much of the cost information considered in this section was obtained from the deployment plan for the Vadose Zone Monitoring System installation at the SRS (Savannah River Site 1998). The drilling and well installation costs are based on recent subcontracts and experience with drilling shallow wells at SRS. The sampling costs are based on the current subcontract with the vendor providing sampling services for the SRS; analytical costs are based on commercial laboratory quotes. Additional detailed AT cost data was provided by J. M. Hubbell, INEEL. That information, provided in Appendix B of this report, addresses the cost of materials and fabrication, based on bids from suppliers and the commercial AT manufacturer. Estimates of installation times, installation materials, and field operation and maintenance requirements were provided by Hubbell and Sisson, based on field experience.

Assumptions

- The advanced technology approach includes ATs, TDR moisture monitors, and suction lysimeters.
- The baseline approach includes a combination of conventional tensiometers, TDR moisture monitors, and suction lysimeters, plus sampling and analysis of groundwater samples from monitoring wells.
- The example application site considered for the cost analysis is at the SRS. Except for drilling costs, the technology application costs at other sites are assumed to be similar to those at the SRS.
- Some site personnel and technical consultant costs occur only in year one. Other site personnel costs (technical assistant, field oversight, and technical oversight) occur at a higher level in year one and at lower levels in the outyears. The estimated levels are indicated in the cost tables presented below.
- The numbers of wells and instruments required to accomplish appropriate levels of characterization and monitoring are similar to the numbers employed in Phase IA of the Vadose Zone Monitoring System deployed at the SRS.
- Sampling for the VZMS devices is assumed to begin the year after installation, providing confidence that the instruments in the vadose zone have had more than enough time to equilibrate.
- The groundwater monitoring wells are sampled quarterly and the samples are analyzed for gross alpha, nonvolatile beta, and tritium. Sampling costs are estimated for wells inside a radiological buffer area and include all related tasks (i. e., sample container preparation, sampling, packaging, and shipment). Sampling and analysis costs are based on estimates from current SRS subcontracts.
- Costs for site characterization, if necessary, are not considered in the cost analysis because they would be the same for the advanced technology approach and the baseline approach.

Cost Analysis

Table 2 lists and provides costs for the items required to characterize and monitor soil water movement in the vicinity of an existing waste disposal facility. Items are listed for both the advanced technology approach (including the use of the ATs addressed in this report) and the baseline technology approach (using conventional tensiometers and groundwater monitoring wells). In both cases the tensiometers are applied with TDRs and suction lysimeters. The numbers of items listed are the actual numbers reported by Burns et al. for the deployment example, Phase IA of the Vadose Zone Monitoring System at the Savannah River Site.

Table 3 shows the estimated sampling and analysis costs for the suction lysimeters and groundwater monitoring wells employed in the advanced technology approach and the baseline technology approach.

Tables 2 and 3 generally include sufficient number and cost information to support cost estimates for larger scale implementations than considered in the present cost analysis. Some site personnel costs will not change much for larger installations (program planning, permitting), whereas other personnel costs will be larger for larger systems.

Tables 4 and 5 show the estimated five-year life cycle costs for application of the advanced technology approach (including ATs) and the baseline technology approach, respectively.

Table 2. Items and costs for advanced technology and baseline approaches for characterization and monitoring of soil moisture movement at an example waste disposal facility.

Item Description	Total required	Cost /each	Total cost
Vertical boreholes (to 60 feet (18.2 m) bgs)	3	$ 5,000	$ 15,000
Angled boreholes (to 60 ft (18.2 m) bgs)	4	$ 700	$ 2,800
4 ATs per vertical borehole	12	$ 500	$ 6,000
4 TDRs per vertical borehole	12	$ 300	$ 3,600
2 suction lysimeters per vertical borehole (shallow type)	6	$ 200	$ 1,200
2 suction lysimeters per vertical borehole (deep type)	6	$ 400	$ 2,400
1 lysimeter per angled borehole	4	$ 400	$ 1,600
Instrument shelters & solar powered data loggers	3	$ 5,000	$ 15,000
Conventional tensiometers (maximum depth = 1.5 m bgs)	3	$ 80	$ 240
Groundwater monitoring wells	4	$ 10,000	$ 40,000

Table 3. Estimated suction lysimeter and groundwater monitoring well sampling and analysis costs.

Item Description	Number of lysimeters	Samples /lysimeter /year	Total samples /year	Total annual cost
Sampling of lysimeters @ $115/each	16	4	64	$ 7,360
Analysis of lysimeter samples @ $120/each	16	4	64	$ 7,680
	Number of wells	Samples /well/year		
Sampling of groundwater monitoring samples @ $115/each	4	4	16	$ 1,840
Analysis of groundwater monitoring samples @ $120/each	4	4	16	$ 1,920

Table 4. Estimated five-year life-cycle costs for implementation of the advanced technology approach (including Advanced Tensiometers) for the example application.

Item Description	Year 1	Year 2	Year 3	Year 4	Year 5
Site personnel (prog. planning, permitting = 1/6 FTE)	$ 30,000	$ -	$ -	$ -	$ -
Site personnel (technical assistant = 1/2 FTE -> 1/4 FTE)	$ 50,000	$ 25,000	$ 25,000	$ 25,000	$ 25,000
Site personnel (field oversight = 1/6 FTE -> 1/12 FTE)	$ 20,000	$ 10,000	$ 10,000	$ 10,000	$ 10,000
Site personnel (technical oversight = 1 FTE -> 1/6 FTE)	$ 150,000	$ 25,000	$ 25,000	$ 25,000	$ 25,000
Technical consultant	$ 50,000	$ -	$ -	$ -	$ -
Drilling (VZMS)	$ 17,800	$ -	$ -	$ -	$ -
Equipment	$ 29,800	$ -	$ -	$ -	$ -
Installation (included in site personnel, above)	$ -	$ -	$ -	$ -	$ -
Sampling & analysis (lysimeters)	$ -	$ 15,040	$ 15,040	$ 15,040	$ 15,040
TOTAL COST	$ 347,600	$ 75,040	$ 75,040	$ 75,040	$ 75,040
TOTAL ACCUMULATED COST	$ 347,600	$ 422,640	$ 497,680	$ 572,720	**$ 647,760**

Table 5. Estimated five-year life-cycle costs for implementation of the baseline technology approach for the example application.

Item Description	Year 1	Year 2	Year 3	Year 4	Year 5
Site personnel (prog. planning, permitting = 1/6 FTE)	$ 30,000	$ -	$ -	$ -	$ -
Site personnel (technical assistant = 1/2 FTE -> 1/4 FTE)	$ 50,000	$ 25,000	$ 25,000	$ 25,000	$ 25,000
Site personnel (field oversight = 1/6 FTE -> 1/12 FTE)	$ 20,000	$ 10,000	$ 10,000	$ 10,000	$ 10,000
Site personnel (technical oversight = 1 FTE -> 1/6 FTE)	$ 150,000	$ 25,000	$ 25,000	$ 25,000	$ 25,000
Technical consultant	$ 50,000	$ -	$ -	$ -	$ -
Drilling (VZMS)	$ 17,800	$ -	$ -	$ -	$ -
Equipment (3 conventional tensiometers instead of 12 ATs)	$ 24,040	$ -	$ -	$ -	$ -
Installation (included in site personnel, above)	$ -	$ -	$ -	$ -	$ -
Sampling & analysis (lysimeters)	$ -	$ 15,040	$ 15,040	$ 15,040	$ 15,040
Drilling (groundwater monitoring wells)	$ 40,000	$ -	$ -	$ -	$ -
Sampling & analysis (groundwater monitoring wells)	$ -	$ 3,760	$ 3,760	$ 3,760	$ 3,760
TOTAL COST	$ 381,840	$ 78,800	$ 78,800	$ 78,800	$ 78,800
TOTAL ACCUMULATED COST	$ 381,840	$ 460,640	$ 539,440	$ 618,240	**$ 697,040**

Cost Conclusions

The cost estimates provided in Tables 4 and 5 show two key things:

1. The five-year life-cycle cost of the advanced technology approach (including the application of ATs) is less than that of the baseline approach—$647,760 versus $697,040—a cost savings of 7%.
2. The largest cost differences between the two approaches occur because the baseline approach uses conventional tensiometers and sampling and analysis of groundwater monitoring wells, whereas the advanced technology approach uses ATs and does not use sampling and analysis of groundwater monitoring wells. The conventional tensiometers are much less expensive than the ATs, $80 per each versus $500 per each, but the estimated cost of each groundwater monitoring well is $10,000 and the estimated cost of quarterly sampling and analysis of each such well is $940. Therefore, if many groundwater monitoring wells are needed to distinguish contamination escaping from a target waste disposal facility from existing contamination from other facilities in the vicinity (as in the SRS E-Area case), then the cost of the baseline approach becomes much more expensive than the advanced technology approach.

Additional Cost Comments

The AT equipment costs are expected to decrease as more instruments are manufactured. The installation and operating costs will also decrease as site personnel become more familiar with AT installation and application.

According to the deployment plan for the VZMS at the Savannah River Site (Savannah River Site 1998), “A potential cost avoidance of $1 to 3 million could be realized annually by ensuring the acceptability of increased trench disposal instead of the more costly vault disposal.” The cost avoidance calculation estimated savings for trench disposal over vault disposal at $30 per cubic foot and an estimated annual volume of waste disposed of 400,000 cubic feet.

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

There are no regulatory or permitting issues specific to the AT or its performance. Site-specific regulatory or permitting issues may arise when ground penetrations are made for the installation of an AT, particularly by drilling. However, no new permitting issues specific to the AT are expected.

Likewise, there are no worker safety issues specific to the AT. The ordinary safety precautions related to heavy equipment and/or drilling equipment are appropriate if such equipment is present when workers are in the field for installation or maintenance of an AT. Actually, as compared to the baseline, ATs require less worker attention for field maintenance because they:

- Require less frequent recharging with water.
- Ordinarily automatically record the data on a data logger.
- Offer the possibility of remotely controlled downloading of measurement results from the data logger by telephone.

Regulatory considerations related to the generation of secondary wastes are not impacted by use of the AT.

Evaluation of the AT with Respect to CERCLA Criteria

1. Overall protection of human health and the environment. The use of ATs is expected to provide better knowledge, understanding, and control of water and contaminant migration, to groundwater, in the vicinity of current and proposed waste storage and waste disposal sites. This should enhance the overall protection of human health and the environment. This is expected because of the ability of ATs to provide data at depths greater than 3 to 7 meters and their decreased maintenance requirements as compared to conventional tensiometers.
2. Compliance with ARARs (Applicable or Relevant and Appropriate Requirements). Not applicable.
3. Long term effectiveness and permanence. The characterization and monitoring enabled by use of ATs is expected to enable better knowledge and understanding of soil moisture and contaminant migration in the subsurface. This is expected to promote consistently more effective and permanent disposal practices.
4. Reduction of toxicity, mobility, or volume through treatment. See item 3, immediately above.
5. Short term effectiveness. The improved characterization and monitoring enabled by use of ATs is expected to reduce the time (and impacts on human health and the environment) until treatment (safe disposal) objectives are achieved.
6. Implementability. The numerous demonstrations and applications of ATs conducted so far show that there is no particular technical difficulty or uncertainty associated with the use of these instruments.
7. Cost. Cost considerations for the AT are addressed in Section 5 of this report.
8. State (support agency) acceptance. Technical and administrative issues and concerns the State (support agency) may have are addressed in the preceding subsection of this report.
9. Community acceptance. Positive community reaction is expected because the AT provides better knowledge and understanding of soil moisture and contaminant migration in the subsurface near waste storage and disposal sites.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Conventional tensiometers are not widely used to help understand soil moisture and contaminant migration at waste storage and disposal sites because they do not perform well at depths greater than 3 to 7 meters. If ATs, which do perform well at greater depths, are used at those sites, worker safety will be impacted by greater exposure to drilling equipment and other heavy equipment that may be present in the field.
- The use of ATs will likely decrease worker exposure and hazards associated with the baseline method of providing compliance assurance—sampling and analysis of groundwater monitoring wells. With better knowledge and understanding of soil moisture and contaminant movement in the subsurface, fewer monitoring wells may be required.

Community Safety and Potential Environmental Impacts

- In contrast to conventional tensiometers, and in contrast to the baseline approach, ATs will help prevent the transport of contamination from storage and disposal sites to the groundwater, thus increasing community safety and minimizing environmental impact.
- In contrast to conventional tensiometers, and in contrast to the baseline approach, ATs can provide early detection of soil moisture (and potential contaminant) migration toward the groundwater. Early detection will allow early action to forestall contamination of the groundwater.

Liability Risk

- ATs will reduce liability risk by providing continuous data on the movement soil moisture in the immediate vicinity of waste storage and waste disposal facilities. The data can show that soil moisture is not transporting contaminants from the waste storage or disposal facility to the groundwater.
- The capability for early detection of soil moisture migration provided by ATs also reduces liability risk because it supports early action to forestall groundwater contamination.

Potential Socioeconomic Impacts and Community Reaction

- Community reaction is expected to be positive because application of the ATs at DOE sites will provide much more complete information than has been availably previously concerning soil moisture movement in the subsurface.
- The long-term monitoring capability of the ATs, particulary with respect to the subsurface soil moisture from episodic infiltration events such as snowmelt or local flooding, is also expected to generate positive community reaction.
- Regulators, stakeholders, and DOE waste site managers will likely request the application of ATs to help demonstrate compliance with DOE Orders regulating disposal of low-level radioactive waste.

Comparison with Baseline and Competing Technologies

- AT measurements have been (and will be) validated through direct comparison with conventional tensiometers at shallow depths and with the results from neutron methods and water content monitors. A record of acceptable performance earns regulatory acceptance.
- Because of the lower life-cycle cost, more complete information provided, and early warning capability, ATs will be perceived as an important improvement over groundwater monitoring wells for monitoring the performance of low-level radioactive waste disposal facilities.

SECTION 7

LESSONS LEARNED

Technology Selection and Implementation Considerations

The deployment of ATs as part of the VZMS installation at the Savannah River Site involved the AT principal investigators in the fabrication, installation, and initial maintenance of the ATs. It is likely that future AT applications will have increased likelihood of success if they also draw upon the practical knowledge and experience of the PIs. This may be accomplished by direct involvement of the PIs and through the use of print and video educational tools.

The VZMS project at the SRS produced a number of observations and recommendations that relate to technology selection and implementation. As can be seen below, some relate directly to AT application.

- The data provided by the monitoring instruments (ATs included) are transmitted to analysts at SRS and INEEL on command (via modem and cellular telephone). Although not shown specifically in the conservative cost estimate provided in the previous section, such data transmission is expected to provide a significant cost avoidance over the long duration of the planned monitoring because field mobilizations are not required for the data taking.
- Each installation should be designed for the site based on monitoring requirements, the geology and vadose zone hydrology. Existing data can and should be used where available.
- Multiple instruments and different measurement methods can be used to improve the reliability and confidence with which critical parameters are determined (for example, use multiple suction lysimeters, TDRs, or tensiometers at important measurement locations; use neutron probe measurements as well as TDR measurements for soil moisture content).
- Instrument life and field maintenance, repair, and replacement should be considered in the selection of monitoring devices.
- The use of access ports should be increased, to facilitate the use of multiple technologies.
- The use of cased boreholes should be considered, to allow instrument replacement in case of failure.
- Pre-deployment planning should consider all phases of monitoring in the system design: pre-operational (installation), operational (including maintenance), and post-operational (e. g., recovery and reuse).
- Investigators should establish a baseline to definitively distinguish between background radiation and that contributed by the disposal area.
- Statistical analyses should be used to quantify uncertainty in measurements and observations.
- A sufficient number of independent (spatially and temporally) measurements is required to calculate bounded estimates of the accuracy and precision of both critical hydraulic parameters and predicted contaminant concentrations.

Technology Limitations and Needs for Future Development

ATs have been used successfully at depths as great as 146 meters (480 feet) bgs, at an INEEL site. The maximum depth at which they will perform reliably has not yet been determined.

The most commonly employed AT design requires field maintenance approximately once every three months, to refill the porous cup with water[10]. A field check of the pressure transducer calibration can be performed at the same time. It appears that another AT design, including electrically operated valves (U. S. patent pending), might have even lower field maintenance requirements because the refilling and calibration checking could be performed automatically or under remote control. Future development focused on the design and performance of such ATs appears to be a worthy endeavor. Expected benefits include increased reliability of AT measurements and considerable personnel cost avoidance from reduction of field mobilization and field maintenance costs.

[10] Depending on local site conditions, the field maintenance period may be as short as one month or longer than one year.

APPENDIX A

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APPENDIX B

ADDITIONAL AT DETAILS AND COSTS

AT Equipment Costs

The heart of the Advanced Tensiometer for Vadose Zone Monitoring (AT), the portion that is permanently installed in the borehole, is comprised of a porous cup, an adapter, and PVC pipe that extends to the land surface. The cost of the porous ceramic is between $5.00 and $20.00 each depending on its size and porosity. The adapter can be manufactured in lots of 100 for approximately $10.00 each. The PVC pipe that extends to land surface is about $0.16 per meter. The total cost of the outer guide pipe, adapter, and porous cup assembly (Figure 2b) is approximately $35.00 for a 15-meter borehole. Additional sizes can be used with only minor changes in overall costs. If smaller diameter instruments are used, the cost is generally lower; if larger diameter instruments, then the cost is slightly greater.

The AT comes in several versions, each with a somewhat different manufacturing cost. The most common (standard) version has a 35.56-mm (1.4-inch) diameter porous ceramic cup with PVC tubing to the land surface. A second version has a stainless steel porous cup and either stainless steel tubing or PVC tubing to the land surface. A third version is a stainless steel drive point model that can be deployed with a cone penetrometer (direct push technology). The casing used in this third version is either PVC or metal.

The AT (excepting the stainless steel drive point version) has been designed to use readily available parts that can be shipped conveniently in small containers. Generally, the pipes can be purchased from local plumbing suppliers.

When offered for sale by a commercial supplier, the cost of an AT was approximately $235.00; this included a permanently installed stainless steel adapter that fit the provided pressure transducer. The cost of the stainless steel adapter is estimated at about one half the total cost.

Pressure Transducer Costs

The pressure transducers used in the AT are field replaceable and interchangeable. Several different forms have been produced.

- A pressure transducer has been constructed in-house at a cost of approximately $30 each, in lots of 100. This design requires tubing, at approximately $0.33 per meter, and miscellaneous items totaling approximately $15. It requires about 3 hours time for fabrication and calibration.
- The pressure transducer first offered for sale as an AT component sold for approximately $1,000. The company charged $13 per meter for the cable from the transducer to the land surface. This cable connected to a $3,000 proprietary data logger provided by the same company. The data logger could monitor as many as eight tensiometers.
- Other low cost pressure sensors, $300 to $700, are available from other manufacturers; cable for $3.25 to $6.50 per meter.
- One manufacturer produces a pressure transducer with integral guide pipe for $250 to $300, with additional cost of approximately $0.82 per meter for cabling. This pressure transducer also requires an adapter stopper at approximately $5 each.

Data Logger Cost

The cost of a typical data logger installation, including, e. g., a Campbell Scientific 23X Data Logger (12 differential analog inputs) and enclosure with modem, battery, tripod, and solar panel for unattended operation plus a cellular telephone, is approximately $6,000. The cost of the commercial cellular telephone service is approximately $300 per year.

Installation Costs

The time required for AT installation is approximately 3 to 6 hours for four instruments at depths of up to 15 meters. Installations at depths greater than 15 meters generally take longer because of the need to tremie the backfill materials to depth.

The cost of installation is primarily for personnel and rig time. Generally it takes two or three people to install instruments and place backfill material. ATs installed at greater depths have greater weight (because of the additional lengths of pressure transducer cable and inner and outer pipes). At depths greater than 15 meters, a rig or some sort of apparatus may be required to assist in lowering the AT.

Three persons can generally assemble and install four ATs in a 15-meter deep borehole in 6 hours. Assuming a cost of $30.00 per person, the total personnel cost for installation of those four ATs is $540.

The costs for backfill materials vary widely depending upon the quantities used. In large quantities, bentonite and hydrated silica flour cost about $100.00 per ton; in very small quantities, up to $5.00 per pound. A single AT installation in a six-inch borehole requires approximately 100 pounds of sand, 100 pounds of silica flour and 400 pounds of bentonite.

The installation of the pressure sensors and the data logger usually takes one to two hours per well. The logger is in an environmental box that needs to be bolted to a pipe of some sort. If an equipment box is required, the total installation time will be close to two hours. The cost of equipment boxes constructed at INEEL is approximately $400.

Maintenance Costs

Approximately once every one to three months (depending on local site conditions), the tensiometer is refilled with water by lifting up the inner guide tube and pressure transducer and allowing water to flow into the porous cup portion of the instrument. Then the stopper/pressure transducer is pushed down and the instrument is back in operation. Six or seven instruments can be refilled with water in a matter of 10 to 15 minutes.

The pressure transducer zero point should be checked and recorded periodically to track any drift in the pressure transducer measurements. It is generally convenient to do this at the same time the AT is refilled with water. The zero point check takes about 5 to 15 minutes per instrument.

Downloading the data logger is generally a 10 to 15 minute operation. As noted in Section 2, this can be done in the field, to a laptop computer, or by remote control via modem and telephone communication with a remote computer.

Data Analysis

The amount of time for data analysis depends heavily on the planned use of the results. Most data files can be collected using standard software such as Microsoft Excel, and most analysis can performed with this software. The AT data analysis cost is not considered in the cost analysis presented in this report.

APPENDIX C

ACRONYMS AND ABBREVIATIONS

AT	Advanced Tensiometer for Vadose Zone Monitoring
bgs	below ground surface
cm	centimeter
DOE-EM	U. S. Department of Energy, Office of Environmental Management
FTE	Full-Time Equivalent
INEEL	Idaho National Engineering and Environmental Laboratory
IRC	INEEL Research Center
m	meter
ml	milliliter
PI	Principal Investigator
PT	Portable Tensiometer
PVC	polyvinyl chloride
SRS	Savannah River Site
TMS	Technology Management System